Solar energy potential on roofs and facades in an urban landscape

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Abstract

A solar 3D urban model was developed for the calculation and visualisation of the solar energy potential of buildings, integrating the potential of roofs with that of facades. To assess this potential, a digital surface model (DSM) of the urban region was built from LiDAR data and a solar radiation model based on climatic observations was applied. A shadow algorithm was developed in order to calculate shadow maps and sky view factor both for roofs and facades at once. Direct and diffuse solar radiation was then obtained for each point on the ground, roof and facades with a spatial resolution of about 1 m and a time resolution of 1 h. This method was applied to a case study of the Campus of the University of Lisbon. Results show that the irradiation reaching facades is lower than that of the roofs, as expected, but due to the large areas concerned, facades have a significant impact on the solar potential of buildings in an urban area.

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1. Introduction

The successful deployment of photovoltaic (PV) systems in urban environments, where a significant fraction of the energy demand is located, requires the assessment of local PV potential. This depends directly from the local exposure to sunlight, which changes drastically in the urban landscape. In fact, the irradiation striking a spot over a time period varies according to global, local, spatial, temporal, and meteorological factors. An ideal solar potential model has to take all these factors into account. At the city or even more local scale, the use of geo-referenced urban fabric models associated to solar radiation tools to determine the incoming solar radiation is particularly interesting since it allows modelling inclined surfaces, while taking into account shadows from surrounding buildings or other topographic features. Several solar radiation models have been implemented in proprietary as well as in open source software. Well known examples are the ArcGis Solar Analyst (Fu and Rich, 1999) and the GRASS r.sun (Hofierka and Súri, 2002). These models can work on a raster based geographic information layer, allowing consideration of spatially changing attributes in the radiation model, such as inclination, orientation and latitude over large regions. They have been successfully used to determine the solar potential of an entire region based on a digital terrain model (Hofierka and Kanuk, 2009) at the municipal level (Nguyen and Pearce, 2012) and the potential in a city department based on roof geometry (Brito et al., 2012).

However, a cityscape includes also the non negligible surfaces of facades, which can be used for collecting sunlight. In modern cities, facades are much larger than roofs, are mostly devoid of building infrastructure (chimneys, elevator engines, ventilators) and usually present better
maintenance conditions for PV panels since vertical surfaces do not accumulate so much dust and are seldom covered by snow in the winter. Furthermore, the European Directive 2010/31/EU establishes that from 2020 onwards, all new buildings will have to be Nearly Zero Energy Buildings, requiring that the local energy production has to cover the local energy demand, which will entail the need for much larger PV areas than those available on standard apartment block roofs (Scognamiglio and Røstvik, 2012). In addition, vertical PV facades will produce relatively more power in winter and less in summer, and more in the early and late hours of the day, when the sun is lower in the sky. Typically, a building will have four, or at least two, exposed facades with opposite orientations and therefore the different solar facades of a building will produce at maximum power at different hours of the day. This effect will lead to a widening of the peak of power production through the day/year which allows a better adjustment to the load diagram, thus enabling significant savings regarding electricity storage and/or fossil fuel based backup power reduction.

The above mentioned solar radiation models are generally not able to consider the facades of the buildings since the facades correspond to (vertical) discontinuities in the 2.5D digital elevation models they are based on. In such a model, vertical facades are represented as more or less inclined surfaces or just disappear all together, not allowing any trustworthy calculation on them. Yet Carneiro (2011) refers an approach for the facades using 3D Urban Models, this requires the pre-existence of such models and involves separated calculation just for facades. One ought to mention that windows are, of course, common features in facades but are not necessarily impeditive of the installation of solar panels, in particular as BIPV (building integrated photovoltaics) become easily accessible (Jelle et al., 2012).

The algorithm presented below calculates the solar irradiation in every point on the roofs, ground and facades, for every hour of the typical meteorological year and thus enables the assessment of the impact of facades on the PV peak power. Furthermore, it only requires the input of a geo-referenced regular height grid describing the relief of an urban site and containing all shadow relevant objects, a digital surface model (DSM), and it simultaneously calculates diffuse, direct, and global solar irradiance for all points of the cityscape at any instant of time, allowing for the computation of the irradiation over any period of time, from 1 h to 1 year. Since such height grids in urban environments can be nowadays easily obtained by airborne Light Detection And Ranging (LiDAR) surveys, the developed algorithm was optimised for this type of 3D data.

2. Method

The algorithm, named SOL, starts from the LiDAR data of the urban region. Together with solar radiation and solar astronomical models it calculates the global solar irradiance for a set of points located on roofs, ground and facades with a spatial resolution of about 1 m and a time resolution of 1 h. The whole process is summarised in the workflow shown in Figs. 1 and 2. Although the algorithm simultaneously tackles roofs, ground and facades, for the sake of a better understanding, the workflow of roofs and ground processing (Fig. 1) and for facades (Fig. 2) are shown separately. In the following four sections inputs and outputs will be described as well as each of the most relevant steps.

2.1. Urban relief model

Urban environments are geometrically characterised as having strong variable heights and steep slopes caused by the existence of buildings of different height limited by vertical walls and separated by more or less narrow streets. In terms of solar energy assessment one can classify urban objects as ground, buildings and trees. The ground is not only interesting for solar potential study when planning the location of structures yet to be built, but its relief (natural or manmade) influences also the solar potential of other objects due to cast shadows and sight obstructions, especially in urban environments with high amplitude terrain. Trees are considered in this study as solid shadow casting objects and their own solar potential will not be considered. Buildings are actually the most relevant urban objects from the solar energy point of view. They have to be both considered as shadow casting objects, over other buildings and over the ground, and as solar collectors. Buildings are composed by roof and facades whose geometric complexity has an influence in the local PV potential. The three kinds of urban objects are considerably well depicted in airborne LiDAR data. Although some details on facades, such as balconies, are not detected in this kind of data due to the view geometry of the sensor, the simplification done in this study of considering the most exterior facade of the building as a vertical planar surface does not reduce significantly the scope of the conclusions due to the relative high spatial density of 1 m and the local scale of the study. All facades that are far from being vertical are treated either as inclined roofs, for outwards slope, or as vertical facades in the rare case of inwards slope.

LiDAR data caught from an airborne platform (plane or helicopter) are a very dense source of height information. They are originally captured in parallel strips along the platform trajectory by emitting an infrared laser beam that is reflected on the ground. The return of each pulse reflected from the ground or from the objects on the ground allows determining the pulse time of flight that can be transformed in distance between emitter and reflecting point. Associated with positioning and navigation data from a GNSS/IMU instrument, installed on the platform, and with the actual emitting angle of the pulse, the 3D coordinates of each reflecting point can be determined.
The set of all reflecting points captured during the flight originates a geo-referenced 3D point cloud of the ground and objects on the ground as seen from above. The data set used in this study is an excerpt of a 2006 LiDAR DSM provided by LOGICA with a dimension of about $400 \times 400 \text{ m}^2$. Elevation and intensity of the first and last pulse returns from a TopoSys II 83 kHz LiDAR instrument, flown on a helicopter, were recorded for each laser pulse, with an average measurement density of 20 points per $\text{m}^2$. The data are re-sampled for a $1 \times 1 \text{ m}^2$ raster and present a documented horizontal accuracy of 0.5 m and a vertical accuracy of 0.15 m (Leitão et al., 2008). It is a typical urban data set containing the buildings of the Faculty of Sciences, associated institutes, a museum and some neighbouring houses as well as part of the tree canopy of an urban park and the museum’s garden with some very high trees. Interesting architectural elements, like court-yards and ramps on the roof are contained in this data set, which can be used to test the coherence of the model.

From the LiDAR DSM inclination (slope) and orientation (aspect) maps with the same resolution were generated. In the slope map all pixels presenting a slope greater than $72^\circ$, which in an urban environment corresponds most probably to vertical walls, were artificially set to $90^\circ$, representing in this way vertical elementary surfaces of $1\text{ m}^2$ in the following steps. From the so manipulated slope map, a binary facade map was generated where all pixels with $90^\circ$ were set to 1, depicting the location of facades, while the remaining pixels became zero.

### 2.2. Solar radiation model

The solar radiation model used in this study is the typical meteorological year data set associated to the SOLTERM database (Aguiar, 1998) which includes hourly mean values for horizontal direct and diffuse irradiation calculated over 30 years from climatic observations. Since it is derived from observations, it includes the influence of clouds. The data are available as tables with hourly values for every day in 1 year and are compiled for each administrative district. The values read on the table have to be integrated in the calculation to be converted in local irradiation according to inclination, orientation, shadow and sky view factor. Alternatively, one could also proceed with empirical solar radiation models such as that of Kumar et al. (1997).

The direct irradiance $B_{\beta \gamma}$ on an inclined surface with inclination $\beta$ and orientation $\gamma$ is given by Eq. (1) where

![Diagram](image-url)
$B_h$ is the beam irradiance on the horizontal plan (which is available from the SOLTERM database). The sun elevation $\alpha$ and the sun azimuth $\gamma_s$ which at a given time are assumed constant for the whole map area are given by Eqs. (2) and (3) (Astr. Alman., 2011).

$$B_{Bh} = B_h (\cos \beta \sin \alpha - \sin \beta \cos \alpha \cos (\gamma_s - \gamma))/ \sin \alpha \tag{1}$$

$$\alpha = \arcsin(\sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi) \tag{2}$$

$$\gamma_s = \arccos\left(\frac{\sin \delta \cos \phi - \cos \delta \cos \omega \sin \phi}{\cos \alpha}\right) \tag{3}$$

As usual, $\phi$ denotes the local latitude, $\omega$ and $\delta$ are the sun hour angle and the sun declination respectively at the time and day of interest.

### 2.3. Direct irradiation and shadow algorithm

Since solar radiation on the earth surface is composed by the sum of direct and indirect sunlight, which is here considered generally as diffuse, it is essential, for the first portion of the sum, to determine if a particular spot receives direct sunlight or is in shadow at a particular time. Shadow can be considered as a space/time binary variable, i.e. at a given time, a certain surface point will either be illuminated or in the shade. Several approaches can be adopted to calculate shadow maps of the terrain for a specified time. Most of them start with a point of interest in a 2.5D elevation model and search in the direction of the sun, along a specified radius, if there are objects that can
obstruct the path of sun light (Hofierka and Súri, 2002; Jochem et al., 2009). These methods fail for facades since their 2.5D based representation does not allow considering several heights in the same XY location. Carneiro (2011) presents an approach for calculating the shadow on facades by slicing a 3D urban model at several height levels (every 3 m) and applying to each level the shadow algorithm of Ratti and Richens (2004) to determine if the actual storey is visible from the sun’s point of view.

For the present study a new shadow algorithm was developed and optimised for urban landscapes at local scale. The algorithm has the DSM as input as well as the sun elevation and azimuth previously calculated through astronomical formulae (Eqs. (2) and (3)) for every hour of the year. A further input is the facade map, a binary map obtained as described in 2.1. Two output maps with the same dimensions as the DSM are generated: a shadow map initiated with 1s and a facade shadow map initiated with zeros. The algorithm considers the parallelism of sun rays and scans the DSM along every possible parallel profile with an orientation equals to the shadow azimuth (actual sun azimuth plus 180°). In each profile the height of the first pixel (towards the sun) is taken as starting height and the spatial sun ray tangent to that pixel is reconstructed as a straight line with an inclination equal to the sun elevation and an azimuth equal to the shadow azimuth. That ray represents the 3D upper bound of the cast shadow along the profile and limits the shadow height cast from the considered starting pixel. Every map pixel along the profile which height in the DSM is lower than the actual shadow height is considered to lie in shadow and turns to null in the output binary shadow map. When pixel height is higher than shadow height in the actual position, two actions take place: first, the actual pixel height is assumed as the new starting height for the following shadow search along the profile; second, in the facade map it is checked if the actual position is a facade. If so, that means that a facade is struck by the cast shadow and the value of shadow height is stored in the actual XY position of the output facade shadow map. Once all possible parallel profiles have been scanned, guaranteeing that all pixels of the DSM were queried, the shadow map for the ground and roofs is ready, but the facade shadow map, containing the shadow heights in each facade XY location, has yet to be completed as described below.

Applying Eq. (1) to each pixel of the DSM under consideration of the slope and aspect maps, and multiplying the result by the binary shadow map obtained above yields the direct irradiance for all positions on the ground and on roofs. This is done separately for every hour of the year. The values for facades will not be included in the direct radiation map since they need further processing following the approach described in the next paragraph.

In the facade map each facade pixel corresponds actually to a hyperpoint. A hyperpoint is composed by a certain number of points with the same XY and different Z coordinates and represents points along a vertical column of the facade sharing its aspect. At each particular time, an XY hyperpoint in the facade can be exclusively in one of the three following situations: totally in shadow, partially in shadow or totally sunlit. In order to calculate the direct irradiation in each facade point it is necessary to determine the shadow height at each hyperpoint. If its position is partially in shadow, the corresponding facade shadow map position was already filled in the previous steps with the value of shadow height. To determine if the remaining facade hyperpoints are sunlit or in shadow, more information is needed which is both acquired during the scan along the profile and from the already obtained binary shadow map. During the search along the profile in the direction of sun light propagation, all the transitions sun-shadow that coincide with transitions facade-ground (or facade-lower roof) are considered as corresponding to facade hyperpoints that are completely in shadow. The shadow height to be assigned to the pixel in the facade shadow map is thus equal to the DSM height in that location (shadow is as high as the roof). For the remaining facade locations a neighbourhood search is done in the shadow map. If the whole immediate neighbourhood is in shadow (e.g. the top of the building and the ground) there is no way the facade is sunlit, so the DSM value will be assigned to the position as shadow height as well. On the contrary, if the immediate neighbourhood is totally sunlit the facade is considered to be also totally sunlit. Hence, the difference between the DSM and the relative height of the facade is assigned to the map position as shadow height (shadow is as high as the ground). The relative height is the height difference between roof and ground or between roof and another lower roof or terrace. The boundary case for sun elevation of 90° is an exception to this rule, for which all facade hyperpoints in the facade map are considered to be in shadow and the facade shadow map receives the DSM heights in all facade pixels. That case happens only twice a year at noon for latitudes between the Tropic of Cancer and the Tropic of Capricorn and once a year in these tropics, at the solstices.

The generated facade shadow maps for all times are the key for all calculations that follow. They contain, as previously explained, the shadow height for all map positions assigned to vertical facades. Limited by the raster nature of the input data, facades are considered one pixel thick which is acceptable for the objective of determining solar energy potential at this scale.

Each element of a hyperpoint is a vertical elementary surface (slope = 90°) with the same aspect (spatial orientation) as the hyperpoint itself. The direct irradiation at that elementary surface is either null, when the element height is lower than the shadow height, meaning it is actually in shadow, or it is calculated by applying Eq. (1) as for the roofs and ground when the element height is higher than the shadow height.

2.4. Diffuse radiation and sky view factor

The indirect component of the irradiation is composed of reflected light, from other buildings and urban features,
and radiation diffused by clouds and the atmosphere in general. In this model we do not consider reflected light. Diffuse light reaches even locations that are in shadow and its quantity depends on one hand on the radiation amount in the atmosphere, hence indirectly from the sun elevation, and on the other hand from the portion of sky that can be seen from the actual location. In an urban environment that portion of sky has a strong variation within small areas: much more sky can be seen from large open squares and high roofs than from narrow streets or small courtyards surrounded by high buildings. Along a vertical facade the portion of seen sky also varies, which has the general effect of higher storeys being much more illuminated than ground floors. The portion of sky seen from a location depends entirely on the disposition and heights of neighbouring objects (buildings, trees and also terrain). It varies in space but not in time since it does not depend on the position of the sun in the sky. It is called the sky view factor (SVF) of that location and is presented as a normalised value between 0 (total obstruction) and 1 (total view of the sky hemisphere above horizon). The diffuse radiation reaching a location at a particular time can be calculated by multiplying the SVF of that location by the diffuse irradiance at full sky, on a horizontal surface.

The SVF in this study is estimated following the approach of Ratti and Richens (2004). Instead of considering a full radiant sky hemisphere, one distributes light sources over the hemisphere, varying the azimuth all around the horizon and the elevation from the horizon up to the zenith. A variation of 5° in azimuth over the whole horizon and 5° in elevation for each azimuth, starting by 15° up until the zenith, yields a set of 1081 light sources more concentrated near the zenith than near the horizon. This non-uniform disposition is suited to represent diffuse irradiation which is known to have a relevant circumsolar component (Perez et al., 1986). For each light source, characterised by a pair azimuth-elevation, the shadow operator described above is applied to the DSM yielding a binary shadow map and a facade shadow map. The 1081 shadow maps are summed resulting, for each pixel, in the total number of hits of rays coming from all light sources. An estimate for the SVF in each location is obtained by dividing that number by the total number of sources. In this way an SVF map can be done for ground and roofs, which multiplied by the full sky horizontal diffuse radiation for each specific time yields a diffuse radiation map for that time.

To determine the SVF along the vertical facades another approach has to be followed, taking the hyperpoints of the facade map into account. Each facade hyperpoint has so many elements as the relative height of the facade. In this study, as the DSM was a grid with $1 \times 1$ m$^2$ meshes, the same resolution was chosen for the hyperpoint elements: 1 m. Thus, a 9 m high facade vertical column corresponds to a nine element hyperpoint, each one with the same XY and a different Z coordinate. The method starts by initializing the counter of all elements of the hyperpoints with the total number of light sources (1081), assuming they could see the whole sky hemisphere. Then, after each run of the shadow algorithm for a particular light source, the facade shadow map pixels are confronted with the corresponding hyperpoints. Those elements which height is lower than the shadow height in the actual XY position are in shadow relative to that light source. Their counter value is reduced of 1 hit. This is done for every element of every facade hyperpoint. Repeating the same procedure each of the 1081 times the shadow algorithm runs, the results are for each hyperpoint element (each square meter on the facade) the number of times it has been lit by the set of light sources. Dividing this number by the total number of times it could have been lit, one estimates the SVF in that vertical square meter of facade at the actual height. SVF on facades are always equal or smaller than 0.5, since, regardless of its orientation, at most only half of the sky hemisphere can be seen from a vertical facade.

3. Results

The method described above was applied to an area of about 160,000 m$^2$ in the Campus of the University of Lisbon, including 9 main buildings. The annual solar irradiation is shown in Fig. 3. As expected, this image clearly shows that irradiation levels are much higher in roofs and ground, with low inclinations, than on vertical facades. South inclined roofs are particularly favourable for the installation of solar panels, reaching annual irradiation levels above 2.0 MW h/m$^2$/year.

The solar irradiation in all calculated points of the ground, facades and roofs can be queried for several periods of time allowing analysing the solar potential at local and urban scale. Fig. 4 demonstrates the visualisation of the shadow evolution along the day on facades as determined by SOL as an essential factor for direct radiation computation.

Also the evolution along the year (Fig. 5) brings some interesting facts into evidence regarding the PV potential of facades in the study region. In the winter the best
oriented facades (towards south) receive a larger amount of solar radiation per square meter than the roofs. The difference between the PV potential of roofs and of south facing facades reverses in the summer. While roofs present a strong variation between the seasons, the PV potential in the mentioned facades shows a much smaller variation.

The detailed examination of the irradiation distribution on the facades is also interesting. Fig. 6 gives a closer look at some of the buildings and the respective annual irradiation. In general, the output of SOL is very satisfactory, as the model is able to detect regions of low SVF, e.g. inside the courtyards and at lower storeys, being able to describe the non-uniform irradiation on a facade due also to partial shadowing from neighbouring buildings.

Supported by the model results, it is particularly relevant to be able to identify the most interesting facades for the installation of solar systems. As an example, Fig. 7 shows the facades where annual solar irradiation is above 900 kW/m²/year. Once the required facade has been
identified, the detailed view of the model (e.g. Fig. 6B and D) can be used to identify the most favourable locations for the installation of a particular solar system.

A method which is solely based on airborne LiDAR data, such as the one discussed above, does not provide any information on the nature of windows or other
features on vertical walls, or the area associated to them. These may limit the technical solar potential of a particular facade although the use of semi-transparent solar modules could reduce their impact on the available area. The analysis of the impact of windows on the solar potential of facades requires the development of complementary analysis based on photogrammetric methods, for urban scale analysis, or local technical assessment, for a particular facade. For the case study of the University campus, which perhaps cannot be considered to be typical for the urban landscape, it was estimated that windows cover an area of about 10% of the total facade area.

In order to assess the relevance of the facades for the overall solar potential of the area, one can plot the total area that receives a certain amount of annual irradiation, as shown in Fig. 8.

The local roofs are particularly suitable for photovoltaic application: about 50% of the roof area receives more than 1600 kW h/m²/year. The annual irradiation on the vertical facades sprawls from about 300 kW h/m²/year (north facing facades) to about 1000 kW h/m²/year (south facing facades). This difference is to be expected due to the much less favourable inclination of the facades. Fig. 9 shows the total annual irradiation for the locations that receive a certain amount of irradiation. It is essentially the same data as the previous plot, although it shows more clearly the amount of solar energy reaching the roofs.

Although one may argue that vertical surfaces can be interesting for very large scale deployment of grid-connected photovoltaic systems since they produce more power during winter months and during early and later hours of the day when demand is higher, we can assume that the deployment of photovoltaics will take into consideration the local annual irradiation and therefore, in the first approach, it is obvious that roofs ought to have priority for the installation of solar power devices.

Thus, one can calculate the cumulative annual irradiation as a function of covered area, as shown in Fig. 10. To build this plot, all roof and facade points were ordered from the highest to the lowest irradiation and the cumulative irradiation was determined as a function of the used fraction of the total available area. The results show that the 25% best spots (i.e. those with higher irradiations) are almost exclusively located on roofs. Only then the most favourable spots on facades appear.

However, the most interesting result is that if we only considered the roof area, we would get a total potential of about 34 GW h/year but if one adds all the potential of the facades we almost double the total potential, to about 53 GW h/year. Indeed, although the average annual irradiation per unit area on facades is lower than that of the roofs, the much larger area means that a significant 19 GW h/year reach the vertical facades throughout the year. Of course, it is abusive to consider a university campus as representative of an average urban area. However, this feature of a large ratio of facade total area/roof total area holds for most modern cities. In fact, it is expected that this effect would be even more significant in an urban landscape of skyscrapers.
4. Conclusions

This paper describes a method for the estimation of solar potential of all surfaces (roofs and facades) of buildings in an urban landscape with a spatial resolution of 1 m. The method calculates hourly shadow maps and facade shadow maps for the estimation of the direct radiation as well as a sky view factor map and facade sky view factor for the estimation of the diffuse radiation. This methodology can be used for the preliminary analysis of solar potential at the municipal or neighbourhood level, as it shows the hourly solar irradiation on all points of the facades and roofs of existing or planned buildings.

The method was implemented using a solar radiation model based on climatic observations and applied to a case study area on the Campus of the University of Lisbon. The results confirm that the annual irradiation on vertical facades is lower than that of more favourable surfaces (roofs) but that, due to their very large areas, the solar potential of facades is relevant for the overall solar potential of a building and/or an urban area. These results are useful for the development of solar dissemination policies and urban planning.

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References


